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PROBABLE DETECTION OF INTERSTELLAR $C^{13}H^+$

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ABSTRACT

A new interstellar line has been found in the spectrum of ζ Oph at 4232.08 $\pm$ 0.01 Å, which is probably the $R(0)$ (0,0) $A\ {}^1\Pi$–$X\ {}^1\Sigma$ line of $C^{13}H^+$. The equivalent width of this line is measured to be $W = 0.68 \pm 0.14$ mÅ. Together with the neighboring strong line of the normal isotopic species, this yields for the isotopic abundance ratio in the line of sight $[C^{12}]/[C^{13}] = 82\ (+55, -15)$.

By adding together on a digital computer twenty-five spectra of ζ Oph obtained with the coudé spectrograph of the Lick 120-inch telescope, we have attained sufficient sensitivity to reveal interstellar lines only a few tenths of a milliangstrom in equivalent width, or about five times weaker than those detectable on a single high-quality spectrogram. This rather brute-force technique has been employed in order to obtain information on the intensity of the cosmic microwave background radiation from the interstellar lines of CN, CH, and CH^+ (Field and Hitchcock 1966; Thaddeus and Clauser 1966), but the spectra, all obtained at a dispersion of 1.3 Å mm^{-1} with a 25-μ projected slit width and widened to 5 mm, are also a valuable source of information on new interstellar lines unrelated to the problem of the background radiation. The resolving power of the spectrograph at this dispersion and slit width exceeds 100000, and the spectra, all obtained on baked IIaO emulsions, cover the wavelength interval from approximately 3650 to 4320 Å.

To effect the spectral synthesis, plate transmission was automatically measured at intervals of 1 μ and recorded digitally on magnetic tape with the densitometer at the Institute for Space Studies. Similar recording of the intensity calibration accompanying each spectrogram allowed the usual transformation from plate density to intensity to be performed by numerical calculation for each plate in turn. Synthesis of the spectra, with appropriate weighting factors determined by analysis of the plate-grain noise, was then a simple matter of addition in the computer.

Although the plate synthesis has so far been performed only in the immediate vicinity of CN λ3874.6, CH λ4300, and CH^+ λ4232, a new line has already been detected just to the blue of λ4232 that cannot easily be attributed to the common isotopic species of these molecules. It is probably λ4232 of $C^{13}H^+$, a line sought first by Wilson (1948) and recently by Augason and Herbig (1967), in order to determine the important interstellar isotopic abundance ratio $a = [C^{12}]/[C^{13}]$. The terrestrial value of this ratio is $a = 89$, while the equilibrium value in the CNO bi-cycle is $a \approx 4$ (Fowler, Caughlan, and Zimmerman 1967). It has been known for many years that a comparably low ratio is observed in a number of low-temperature carbon stars (McKellar 1965). From a synthesis of three spectra, also of ζ Oph obtained at the 120-inch coudé, Augason and Herbig (1967) were able to set an upper limit of 1.5 mÅ for the equivalent width of λ4232 of $C^{13}H^+$, yielding $a > 30$ for the abundance ratio and thereby suggesting that the C^{13}-rich carbon stars contributed little to the interstellar material in the direction of ζ Oph.

Figure 1 shows the result of the plate synthesis in the vicinity of λ4232, which is the

$R(0)$ line of the (0,0) band of the $A\ ^1\Pi - X\ ^1\Sigma$ system of CH^+ and the strongest interstellar molecular line in the spectrum of ζ Oph. The rest wavelength of this transition is 4232.539 Å, according to the laboratory analysis of Douglas and Herzberg (1942). Its precise wavelength in the -15 km sec^{-1} cloud is 4232.341 Å (Herbig 1968), while Augason and Herbig (1967) calculate its isotope shift for $C^{13}H^+$ to be -0.26 Å. At precisely this displacement, or at a wavelength of 4232.08 ± 0.01 Å, the plate synthesis shown in Figure 1 reveals a weak feature whose equivalent width calculated by numerical integration is $W_{13} = 0.68 \pm 0.14$ mÅ (uncertainty estimated). The signal strength is over three times the standard deviation of the plate-grain noise. Integration over the adjacent line of $C^{12}H^+$ yields $W_{12} = 26.9$ mÅ, in good agreement with the value 27.4 mÅ reported by Herbig (1968) in a recent detailed study of the interstellar-line spectrum of ζ Oph.

Application of the usual significance tests leaves little doubt that this new interstellar feature is real. It is hard to see how it could result from an adjacency effect, and in any case we have not observed spurious lines of this nature in the vicinity of other strong lines

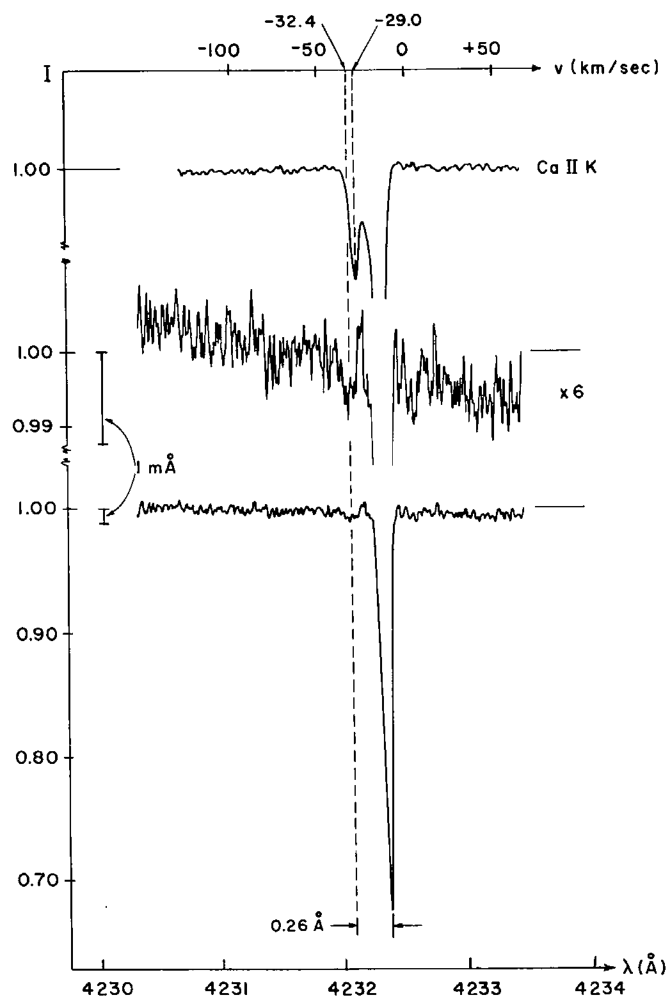

FIG. 1.—Spectrum of ζ Oph in the vicinity of λ4232. The lower spectrum shows the normal interstellar line of CH^+ and the new feature, displaced by -0.26 Å, attributed to $C^{13}H^+$. In the middle trace the vertical scale of this spectrum is increased by a factor of 6, while at the top the K-line of interstellar Ca II is plotted on the same velocity scale in order to show that the new feature is not formed in the -29 km sec^{-1} cloud.

studied by the technique of plate synthesis. However, the possibility that this new line is simply a high-velocity component of the usual CH^+ line deserves serious consideration.

Under conventional high resolution the interstellar absorption lines of Na and Ca II in ζ Oph are double, with a strong component at -15 km sec^{-1} and a weaker one at -29 km sec^{-1} (Herbig 1968). The difference in velocity, -14 km sec^{-1}, corresponds at 4232 Å to a displacement of -0.19 Å, predicting a line that falls about 0.05 Å, or over one resolution element, short of the new feature (see Fig. 1). This discrepancy is sufficiently great to exclude the possibility that this line is wholly produced in the -29 km sec^{-1} cloud, although (as clearly seen at the top of Fig. 1, where the profile of the K-line in ζ Oph is shown at the same velocity scale as λ4232) a blend with a line at this velocity cannot be ruled out. However, under the very high resolving power ($\sim$600000) obtained with a three-étalon Fabry-Pérot (Pepsios) interferometer, Hobbs (1968) has observed still further velocity components to the Na D-lines in ζ Oph, and he finds in particular in D_2 a very weak feature at -31.6 ± 0.2 km sec^{-1}. At 4232 Å this corresponds to a wavelength displacement of -0.25 Å, and thus $C^{12}H^+$ in this cloud could in principle produce a line at virtually the wavelength of the new transition.

We reject this idea, however, on the ground that it would require a density of CH^+ molecules relative to Na atoms considerably higher than has hitherto been observed in an interstellar cloud. Both the -31.6 km sec^{-1} line observed by Hobbs, for which he finds $W(D_2) \approx 1$ mÅ, and the new line considered here are so weak that they can be located with confidence on the linear part of the curve of growth. The ratio of their equivalent widths, $W(\lambda4232)/W(D_2) \sim \frac{1}{2}$, thus represents the ratio of their corresponding optical depths and is proportional in the line of sight to the relative (column) number densities in the cloud. In contrast to this, the -15 km sec^{-1} cloud in ζ Oph yields $W(\lambda4232)/W(D_2) = \frac{1}{9}$, and when proper account is taken of the high degree of saturation of D_2, $\tau(\lambda4232)/\tau(D_2) = \frac{1}{65}$ (Herbig 1968). This is found to be a typical ratio for those clouds in which λ4232 is conspicuous, although there are admittedly few instances where sufficient information exists on the interstellar curves of growth of CH^+ and Na to allow the calculation to be done precisely. However, by taking a reasonable value for the line-width parameter b in the curve-of-growth analysis, say 1–4 km sec^{-1}, it is possible to extract approximate values of $\tau(\lambda4232)/\tau(D_2)$ from available data. Thus, for thirty-four of the sixty-one stars for which $W(\lambda4232)$ was estimated or measured by Adams (1949) or by Rogerson, Spitzer, and Bahng (1959), $W(D_2)$ is also found in the various compilations of interstellar Na and Ca II lines (Merrill *et al.* 1937; Spitzer 1948; Beals and Oke 1953; Münch 1957). Of these, in turn, there are a dozen instances in which the structure of the D-lines (or H- and K-lines) suggests that $W(D_2)$ pertains essentially to one cloud, which on the basis of a common radial velocity is presumably the one in which the CH^+ line is formed. In all these cases we find that $W(\lambda4232)/W(D_2) < \frac{1}{5}$, while the high saturation of D_2 encountered in all instances leads to a considerably smaller ratio of optical depths: $\tau(\lambda4232)/\tau(D_2) < \frac{1}{17}$, if b is taken in the range 1–4 km sec^{-1}. It would clearly be desirable to test this argument further by a systematic observational study of the CH^+/Na ratio in directions (such as that of the Pleiades) where CH^+ is prominent. But the data just cited are sufficiently extensive to convince us that λ4232.08 is unlikely to be a high-velocity component of the usual CH^+ line, and we instead assign this new feature, on the basis of its precise location at the expected isotope shift, to the species $C^{13}H^+$.

Mention should finally be made of a potentially conclusive test for the existence of $C^{13}H^+$ in the spectrum of ζ Oph, which has unfortunately so far yielded quite inconclusive results. This would be detection at 3957 Å of $R(0)$ of the (1,0) $A\ ^1\Pi$–$X\ ^1\Sigma$ band, since the isotope shift of this line is $+0.44$ Å and there is therefore no confusion with known high-velocity clouds. The Franck-Condon factor for this band is favorable, predicting an intensity of λ3957 relative to λ4232 of 0.53 (Herbig 1968). We have searched for this line by synthesizing the spectra at hand in the vicinity of λ3957, but we observed no feature at either +0.44 Å or −31.6 km sec^{-1}. The idea that the isotopic line lies just below the level of detectability is consistent with the observed noise level.

Entering W_{12} and W_{13} in Herbig's (1968) curve of growth for interstellar CH^+ in ζ Oph yields the optical depths $\tau_{12} = 2.61$ and $\tau_{13} = 0.032 \pm 0.007$. If we somewhat pessimistically estimate that as much as one-third of W_{13} may in reality be due to a blend with a $C^{12}H^+$ line at −15 km sec^{-1}, then $\tau_{13} = 0.032$ (+0.007, −0.013), and the abundance ratio in the line of sight is

$$a = \tau_{12}/\tau_{13} = 82\ (+55,\ -15)\ .$$

Clearly this determination strengthens the conclusion that C^{13}-rich carbon stars have not appreciably contributed to the CH^+ molecules, or presumably to the rest of the interstellar material, in the direction of ζ Oph. However, the close agreement between the interstellar ratio and the terrestrial value $a = 89$ now suggests in addition that the composition of the interstellar medium has remained rather stable for at least 5×10^9 years. The only other interstellar isotopic ratio for which there is positive evidence supports this idea. Rogers and Barrett (1966) and Barrett (1967) observed the radio λ-doublet of $O^{18}H$ at about the level to be expected if the interstellar ratio $[O^{16}]/[O^{18}]$ is the same as the terrestrial value 490. Precise evaluation of this ratio, however, is rendered difficult by the anomalous excitation of the OH λ-doublet.

The need for further observational work is clear. The line λ3957 of $C^{13}H^+$ in ζ Oph must be found before we can be absolutely certain of the assignment made in this Letter, and it will be of considerable interest to learn whether $a \approx 90$ prevails in other interstellar clouds. In view of the large amount of observation on which the present work is based, however, and the uniquely favorable interstellar-line spectrum of ζ Oph, it is likely that significant progress along these lines must await further application of photoelectric techniques to the study of interstellar spectra.

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